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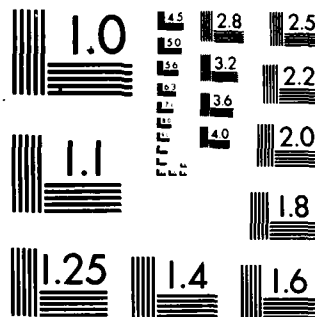
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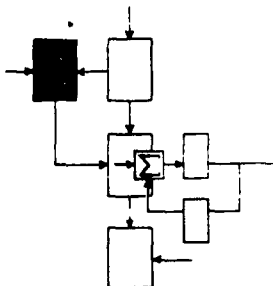
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Progress on six research problems addressing distributed tactical decisionmaking is described. <i>F</i>		



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NAVAL C³ DISTRIBUTED TACTICAL DECISIONMAKING

1. PROJECT OBJECTIVES

The objective of the research is to address analytical and computational issues that arise in the modeling, analysis and design of distributed tactical decisionmaking. The research plan has been organized into two highly interrelated research areas:

- (a) Distributed Tactical Decision Processes;
- (b) Distributed Organization Design.

The focus of the first area is the development of methodologies, models, theories and algorithms directed toward the derivation of superior tactical decision, coordination, and communication strategies of distributed agents in fixed organizational structures. The framework for this research is normative.

The focus of the second area is the development of a quantitative methodology for the evaluation and comparison of alternative organizational structures or architectures. The organizations considered consist of human decisionmakers with bounded rationality who are supported by C³ systems. The organizations function in a hostile environment where the tempo of operations is fast; consequently, the organizations must be able to respond to events in a timely manner. The framework for this research is descriptive.

2. STATEMENT OF WORK

The research program has been organized into seven technical tasks - four that address primarily the theme of distributed tactical decision processes and three that address the design of distributed organizations. An eighth task addresses the integration of the results. They are:



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2.1 Real Time Situation Assessment

Static hypothesis testing, the effect of human constraints and the impact of asynchronous processing on situation assessment tasks will be explored.

2.2 Real Time Resource Allocation

Specific research topics include the use of algebraic structures for distributed decision problems, aggregate solution techniques and coordination.

2.3 Impact of Informational Discrepancy

The effect on distributed decisionmaking of different tactical information being available to different decisionmakers will be explored. The development of an agent model, the modeling of disagreement, and the formulation of coordination strategies to minimize disagreement are specific research issues within this task.

2.4 Constrained Distributed Problem Solving

The agent model will be extended to reflect human decisionmaking limitations such as specialization, limited decision authority, and limited local computational resources. Goal decomposition models will be introduced to derive local agent optimization criteria. This research will be focused on the formulation of optimization problems and their solution.

2.5 Evaluation of Alternative Organizational Architectures

This task will address analytical and computational issues that arise in the construction of the generalized performance-workload locus. This locus is used to describe the performance characteristics of a decisionmaking organization and the workload of individual decisionmakers.

2.6 Asynchronous Protocols

The use of asynchronous protocols in improving the timeliness of the organization's response is the main objective of this task. The tradeoff between timeliness and other performance measures will be investigated.

2.7 Information Support Structures

In this task, the effect of the C³ system on organizational performance and on the decisionmaker's workload will be studied.

2.8 Integration of Results

A final, eighth task, is included in which the various analytical and computational results will be interpreted in the context of organizational bounded rationality.

3. STATUS REPORT

In the context of the first seven tasks outlined in Section 2, a number of specific research problems have been formulated and are being addressed by graduate research assistants under the supervision of project faculty and staff. Research problems which were completed prior to or were not active during this last quarter have not been included in the report.

3.1 DISTRIBUTED TEAM HYPOTHESIS TESTING WITH SELECTIVE COMMUNICATIONS

Background: The goal of this research is to investigate the synthesis of an organization whose objective is to distinguish among several possible hypotheses. Each hypothesis will be characterized by different attributes. Each attribute will have different degree of observability to different decision makers, or teams of decision makers, within the organization. Hence, to reliably confirm a particular hypothesis two or more decision makers will have to pool their knowledge. Also, it will be desirable to

develop the organizational protocols which minimize unnecessary communications among the decision makers. On the other hand, investment in communications will be necessary so as to minimize disagreement among the decision makers. Finally, we would like to include some measure of vulnerability of individual decision makers; such vulnerability considerations will justify the distribution of the decision making process, and the built-in partial redundancy of decision makers observing the same hypotheses attributes.

In the context of Command-and-Control systems, this class of problems arise in target detection and classification (identification and discrimination). Some target attributes, such as position are best observed by radars; however, other target attributes, e.g., identity, are best observed by ESM receivers or other discriminants. Hence, in order to both locate and identify a target out of a possibly large potential population, one must design a distributed hypothesis testing organization of the type discussed above. Vulnerability to enemy actions and countermeasures, such as jamming, must be considered in the design of such organizations.

Problem Statement: A precise mathematical formulation of the several important issues is not available as yet. Indeed the definition of precise mathematical problems that capture in a realistic and relevant manner the key issues will be a major source of difficulty in this class of problems. Once the mathematical distributed decision problems are formulated, then normative/prescriptive solutions will be sought.

Progress to Date: This research problem was initiated during the past quarter. Hence, the research is at the formative stage. It will most probably form the core of the Ph.D. Thesis of J. Papastavrou under the supervision of Professor M. Athans.

Documentation: None as yet.

3.2 DISTRIBUTED HYPOTHESIS TESTING WITH MANY AGENTS

Background: The goal of this research project is to develop a better understanding of the nature of the optimal messages to be transmitted to a central command station (or fusion center) by a set of agents who receive different information on their environment. In particular, we are interested in solutions of this problem which are tractable from the computational point of view. Progress in this direction has been made by studying the case of a large number of agents. Normative/prescriptive solutions are sought.

Problem Statement: Let H_0 and H_1 be two alternative hypotheses on the state of the environment and let there be N agents (sensors) who possess some stochastic information related to the state of the environment. In particular, we assume that each agent i observes a random variable y_i with known conditional distribution $P(y_i | H_j)$, $j = 0, 1$, given either hypothesis. We assume that all agents have information of the same quality, that is, the random variables are identically distributed. Each agent transmits a binary message to a central fusion center, based on his information y_i . The fusion center then takes into account all messages it has received to declare hypothesis H_0 or H_1 true. The problem consists of determining the optimal strategies of the agents as far as their choice of message is concerned. This problem has been long recognized as a prototype problem in team decision theory: it is simple enough so that analysis may be feasible, but also rich enough to allow nontrivial insights into optimal team decision making under uncertainty.

Progress to Date: This problem is being studied by Prof. J. Tsitsiklis. Under the assumption that the random variables y_i are conditionally independent (given either hypothesis), it is known that each agent should choose his message based on a likelihood ratio test. Nevertheless, we have constructed examples which show that even though there is perfect symmetry in the problem, it is optimal to have different agents use different thresholds in their likelihood ratio tests. This is an unfortunate situation, because it severely complicates the numerical solution of the problem (that is, the

explicit computation of the threshold of each agent). Still, we have shown that in the limit, as the number of agents becomes large, it is asymptotically optimal to have each agent use the same threshold. Furthermore, there is a simple effective computational procedure for evaluating this single optimal threshold.

More recently, we showed that if each agent is to transmit K-valued, as opposed to binary messages, then still each agent should use the same decision rule, when the number of agents is large.

We have also investigated the case of M-ary ($M > 2$) hypothesis testing and obtained evidence indicating that different agents should use different decision rules even in the limit of $N \rightarrow \infty$. The questions concerning the nature of optimal decision rules, as $N \rightarrow \infty$ remains open in this case.

We also considered a class of decentralized sequential detection problems and showed that only under certain fairly restrictive assumptions do the optimal decision rules have a nice structure.

Documentation: J. Tsitsiklis, "On Optimal Thresholds in Decentralized Detection," to appear in the IEEE Transactions on Automatic Control and in the Proc. 25th IEEE Conference on Decision and Control, Athens, Greece, December 1986; also Report LIDS-P-1570, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, June 1986.

3.3 COMMUNICATION REQUIREMENTS OF DIVISIONALIZED ORGANIZATIONS

Background: In typical organizations, the overall performance cannot be evaluated simply in terms of the performance of each subdivision, as there may be nontrivial coupling effects between distinct subdivisions. These couplings have to be taken explicitly into account; one way of doing so is to assign to the decision maker associated with the operation of each division a cost function which reflects the coupling of his own division with the

remaining divisions. Still, there is some freedom in such a procedure: For any two divisions A and B it may be the responsibility of either decision maker A or decision maker B to ensure that the interaction does not deteriorate the performance of the organization. Of course, the decision maker in charge of those interactions needs to be informed about the actions of the other decision maker. This leads to the following problem. Given a divisionalized organization and an associated organizational cost function, assign cost functions to each division of the organization so that the following two goals are met: a) the costs due to the interaction between different divisions are fully accounted for by the subcosts of each division; b) the communication interface requirements between different divisions are small. In order to assess the communication requirements of a particular assignment of costs to divisions, we take the view that the decision makers may be modeled as boundedly rational individuals, that their decision making process consists of a sequence of adjustments of their decisions in a direction of decreasing costs, while exchanging their tentative decisions with other decision makers who have an interest in those decisions. We then require that there are enough communications so that this iterative process converges to an organizationally optimal set of decisions.

Problem Statement: Consider an organization with N divisions and an associated cost function $J(x_1, \dots, x_N)$, where x_i is the set of decisions taken at the i -th division. Alternatively, x_i may be viewed as the mode of operation of the i -th division. The objective is to have the organization operating at set of decisions (x_1, \dots, x_N) which are globally optimal, in the sense that they minimize the organizational cost J . We associate with each division a decision maker DM_i , who is in charge of adjusting the decision unables x_i . We model the decision makers as "boundedly rational" individuals; mathematically, this is translated to the assumption that each decision maker will slowly and iteratively adjust his decisions in a direction which reduces the organizational costs. Furthermore, each decision maker does so based only on partial knowledge of the organizational cost, together with messages received from other decision makers.

Consider a partition $J(x_1, \dots, x_N) = \sum_{i=1}^N J^i(x_1, \dots, x_N)$ of the organizational cost. Each subcost J^i reflects the cost incurred to the i -th division and in principle should depend primarily on x_i and only on a few of the remaining x_j 's. We then postulate that the decision makers adjust their decisions by means of the following process (algorithm):

- (a) DM_i keeps a vector x with his estimates of the current decisions x_k of the other decision makers; also a vector λ with estimates of $\lambda_i^k = \partial J^k / \partial x_i$, for $k \neq i$. (Notice that this partial derivative may be interpreted as DM_i 's perception of how his decisions affect the costs incurred to the other divisions.
- (b) Once in a while DM_i updates his decision using the rule $x_i := x_i - \gamma \sum_{k=1}^N \lambda_i^k$, (γ is a small positive scalar) which is just the usual gradient algorithm.
- (c) Once in a while DM_i transmits his current decision to other decision makers.
- (d) Other decision makers reply to DM_i , by sending a updated value of the partial derivative $\partial J^k / \partial x_i$.

It is not hard to see that for the above procedure to work it is not necessary that all DM's communicate to each other. In particular, if the subcost J^i depends only on x_i , for each i , there would be no need for any communication whatsoever. The required communications are in fact determined by the sparsity structure of the Hessian matrix of the subcost functions J^i . Recall now that all that is given is the original cost function J ; we therefore have freedom in choosing the J^i 's and we should be able to do this in a way that introduces minimal communication requirements; that is, we want to minimize the number of pairs of decision makers who need to communicate to each other.

The above problem is a prototype organizational design problem and we expect that it will lead to reasonable insights in good organizational structures. On the technical side, it may involve techniques and tools from graph theory. Once the above problem is understood and solved, the next step is to analyze communication requirements quantitatively. In particular, a distributed gradient algorithm such as the one introduced above converges only if the

communication between pairs of DM's should need to communicate are frequent enough. We will then investigate the required frequencies of communications as a function of the strength of coupling between different divisions.

Progress to Date: A graduate student, C. Lee, supervised by Prof. J. Tsitsiklis, has undertaken the task of formulating the problem of finding partitions that minimize the number of pairs of DM's who need to communicate to each other as the topic of his SM research. The literature search phase has been completed, and different problem formulations are being investigated. Certain preliminary results have been already obtained for a class of combinatorial problems, corresponding to special cases of the problem of optimal organizational design, under limited communications.

Documentation: None as yet.

3.4 COMMUNICATION COMPLEXITY OF DISTRIBUTED CONVEX OPTIMIZATION

Background: The objective of this research effort is to quantify the minimal amount of information that has to be exchanged in an organization, subject to the requirement that a certain goal is accomplished, such as the minimization of an organizational cost function. This problem becomes interesting and relevant under the assumption that no member of the organization "knows" the entire function being minimized, but rather each agent has knowledge of only a piece of the cost function. A normative/prescriptive solution is sought.

Problem Formulation: Let f and g be convex function os n variables. Suppose hat each one of two agents (or decisionmakers) knows the function f (respectively g), in the sense that he is able to compute instantly any quantities associated with this function. The two agents are to exchange a number of binary messages until they are able to determine a point x such that $f(x) + g(x)$ comes within ϵ of the minimum of $f + g$, where ϵ is some prespecified accuracy. The objective is to determine the minimum number of such messages that have to be exchanged, as a function of ϵ and to determine communication protocols which use no more messages than the minimum amount required.

Progress to Date: The problem is being studied by Professor John Tsitsiklis and a graduate student, Zhi-Quan Luo. It is not hard to show that at least $O(n \log 1/\epsilon)$ messages are needed and a suitable approximate and distributed implementation of ellipsoid-type algorithms demonstrates with $O(n^2 \log 1/\epsilon)$ messages. The challenge is to close this gap. This has been accomplished for the case of one-dimensional problems $n = 1$ for which it has been shown that $O(\log 1/\epsilon)$ messages are also sufficient. More recently, we have succeeded in generalizing the technique employed in the one-dimensional case, and we obtained an algorithm with $O(n^2 \log 1/\epsilon)$ communications; we thus have an algorithm which is optimal, as far as the dependence of ϵ is concerned. The question of the dependence of the amount of communications on the dimension of the problem ($O(n)$ versus $O(n^2)$) seems to be a lot harder and, at present, there are no available techniques for handling it.

Another problem which is currently being investigated concerns the case where there are $K > 2$ decision makers cooperating for the minimization of $f_1 + \dots + f_k$ where each f_i is again a convex function.

Documentation: J. N. Tsitsiklis and Z.-Q. Luo, "Communication Complexity of Convex Optimization," Report LIDS-P-1617, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, October 1986; also to appear in the Proceedings 25th IEEE Conference on Decision and Control, Athens, Greece, December 1986.

3.5 DESIGN AND EVALUATION OF ALTERNATIVE ORGANIZATIONAL ARCHITECTURES

Background: The bounded rationality of human decisionmakers and the complexities of the tasks they must perform mandate the formation of organizations. Organizational architectures distribute the decisionmaking workload among the members; different architectures impose different individual loads, lead to different organizational bounded rationality, and result in different organizational performance. Two performance measures have been investigated up to now: accuracy and time delay. An approach to

the evaluation and comparison of alternative organizational architectures, that provides insight into the effect structure has on organizational bounded rationality, is the use of a generalized performance-workload locus.

Problem Statement: The development of design guidelines for distributed organizational architectures is the objective. To achieve this objective, a sequence of steps has been defined. Each step in the sequence requires the solution of both modeling and computational problems:

- (1) Development of efficient computational procedures for constructing the generalized performance-workload locus.
- (2) Analysis of the functional relationship between internal decision strategies and workload (i.e., the properties of the mapping from strategy space to workload space).
- (3) Development of quantitative and qualitative relationships between organizational architecture and the geometry of the performance-workload locus.

Remarks: The work implied in the problem statement requires modeling, analysis, and computation. The use of computer graphics is an integral part of the computational procedures.

At the beginning of this reporting period, the direction of research changed. With the basic tools for the computation of organizational performance developed and implemented, the emphasis has been shifted to formulating the organizational design problem. This task has been divided into two subtasks that correspond to two thesis projects.

(1) Generation of Organizational Architectures

Objective: The objective of this task is the development of analytical and computational tools for the design of distributed organizational architectures that satisfy a number of constraints.

Progress To Date: This task has been carried out by Pascal Remy under the supervision of Dr. A. H. Levis. Major progress has been achieved in this

task during the last quarter. The problem of designing alternative organizational architectures is a combinatorial one, with $2^{4n(n-2)}$ possible organizations, when the number of decisionmakers is n . However, most of these organizations that can be generated in principle in a mechanistic way are not acceptable solutions, i.e., they violate one or more of the assumptions that characterize a distributed tactical decisionmaking organization. For example, there is a minimum degree of connectivity between the decisionmakers that is needed, if they are to form an organization.

The approach taken is not to enumerate and test each possible organizational structure to determine whether it is a feasible solution, but to devise a way of characterizing the set of feasible organizations by the maximal and minimal, in some sense, elements of the set and by an algorithm that generates the elements of the set. The approach was described in the paper "On the Design of Distributed Organizational Structures" by P. Remy, A. H. Levis, and V. Jin which was appended to the previous quarterly report. In this past quarter, two developments are worth noting:

- (a) Refinement of the analytical characterization of the feasible solutions, which has led to improvements in the speed and efficiency of the algorithm.
- (b) Recognition that the set of feasible solutions is a partially ordered set and, furthermore, that it is a lattice. This has opened up a wealth of existing results in lattice theory that are currently being interpreted in the context of the organizational design problem.

The fact that the set of feasible solutions is a lattice provides the foundation for planned work on the very hard problem of classifying alternative structures in terms of their properties. A Ph.D. candidate in Applied Mathematics at MIT, Mr. Joseph Oliveira, has begun looking at this problem in the context of his thesis research. While Mr. Oliveira is not formally associated with this project, a working relationship has been established on the basis of common research interests - his on the abstract

problem of classification of structures and ours on ways for classifying distributed decisionmaking architectures. This is an original line of inquiry that goes beyond what was anticipated in the proposal.

(ii) Design of Organizations

Objective: Given a feasible organizational architecture, develop a methodology for (a) identifying the functions that must be performed by the organization in order that the task be accomplished, (b) selecting the resources (human, hardware, software) that are required to implement these functions, (c) integrating these resources - through interactions - so that the system operates effectively.

Progress to Date: This research problem is being investigated by Stamos K. Andreadakis under the supervision of Dr. A. H. Levis. The proposed design methodology consists of two stages.

In the first stage, the specific objective is to meet the requirements for the two measures of performance - accuracy and timeliness. This is accomplished by selecting the functions that are to be performed by the organization in support of the task. The emphasis in this stage is on the design of the protocols that specify the interactions between the processes that instantiate the functions.

In the second stage, the objective is allocating the various functions to different decisionmakers so that the individual workload constraints are met. The allocation must satisfy additional considerations such as the need for some redundancy so that the system has high degrees of survivability and reconfigurability.

At this time, the two stages of the iterative design process have been specified and the corresponding algorithms have been designed. In the next stage, the algorithms will be implemented and tested on two examples - one based on a five person abstraction of an organization representing the CWC

doctrine and one that address the issues of flexibility and reconfigurability.

Documentation: None as yet. This work is expected to be the core of S. Andreadakis' doctoral thesis.

3.6 COMPUTER GRAPHICS FOR ORGANIZATIONAL DESIGN

Background: The analysis of organizations has been based on the ability to construct the performance-workload locus. This is the locus of points that characterize the performance of an organizational form, as described in Section 3.5. This locus serves as the basis for analysis, evaluation, and design of organizations. Indeed, the computer aided design procedure that is being investigated depends on the ability to construct and manipulate this locus with ease.

Problem Statement: There is need to automate the generation of the performance-workload locus. Furthermore, the use of graphics, will allow one to view and compare loci produced from different organizational forms or different values of the design parameters of the same structure. To produce a software system that allows one to do this, several parts needed to be designed, implemented and tested:

- (1) A data structure which provides an efficient but general way of storing the data generated by diverse applications.
- (2) Software implementation of algorithms for constructing the loci.
- (3) Software implementation of algorithms for viewing the loci in different ways, by rotating, translating, or projecting them.
- (4) An interactive interface for users to control viewing MOP space.

Remarks: The IBM PC/AT with the Professional Graphics system is being used for this work. This includes the Professional Graphics Controller (PGC), the IBM Professional Graphics Display, the IBM Graphics Toolkit Development Software, and IBM Professional Fortran. The PGC consists of an 8088 microprocessor which executes 3-D graphics routines in ROM (read-only memory). The graphics routines are executed to perform rotation of the loci about the center point with the amount of rotation specified by the user. This system produces high-resolution color graphics. High quality color plots can be produced on an HP six-pen plotter (Model HP 7475A). A user's manual is now available.

Progress to Date: The software has been used in two recently completed theses. It became apparent that a better user interface was needed, if the software for constructing loci and for evaluating organizations were to be accessible to other researchers. Vicky Jin, under the supervision of Dr. A. H. Levis, has undertaken a short term project to design a graphics interface that could facilitate use of the software and also be consistent with the interface being developed for the software that generates organizational structures. The need to integrate the various components into a design system, while recognizing the constraints inherent in academic research where different components are developed by different research assistants to serve different needs, has led to the following: (a) standard underlying data structure that represents the organizations so that all programs access necessary data from a common data base and (b) a standardized graphics interface. Progress is being made, but at a slow pace since some revisions of the existing software are necessary to achieve some degree of interoperability. Even though all software operate on the same machine and use the same operating system, the commercial software that is being used is often not easily compatible with each other. This is expected to be a continuing effort, but one that is essential, if the overall goals of the project are to be achieved.

Dpcumentation: None as yet. A user's manual will be developed for release with the tested version of the software.

4. RESEARCH PERSONNEL

Prof. Michael Athans, Co-principal investigator
Dr. Alexander H. Levis, Co-principal investigator
Prof. John Tsitsiklis
Dr. Jeff Casey

Mr. Stamatios Andreidakis	graduate research assistant (Ph.D.)
*Mr. Herve Hillion	graduate research assistant (M.S)
Ms. Victoria Jin	graduate research assistant (Ph.D.)
Ms. Chongwan Lee	graduate research assistant (M.S)
Mr. Jason Papastavrou,	graduate research assistant (Ph.D)
Mr. Pascal Remy	graduate research assistant (M.S)
Mr. Jean Louis Grevet	graduate research assistant (M.S)

*Received M.S. degree

5. DOCUMENTATION

5.1 Theses

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- [2] G. J. Bejjani, "Information Storage and Access in Decisionmaking Organizations," MS Thesis, Technology and Policy Program, also Report LIDS-TH-1434, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, January 1985.
- [3] V. Y.-Y. Jin, "Delays for Distributed Decisionmaking Organizations," MS Thesis, Mechanical Engineering, also Report LIDS-TH-1459, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, May 1985.
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- [8] H. P. Hillion, "Performance Evaluation of Decisionmaking Organizations Using Timed Petri Nets," MS Thesis, Technology and Policy Program, also Report LIDS-TH-1590, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, August 1986.

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- [3] V. Y.-Y. Jin and A. H. Levis, "Computation of Delays in Acyclical Distributed Decisionmaking Organizations," LIDS-P-1488, Laboratory for Information and Decision Systems, MIT, August 1985.
- [4] K. L. Boettcher and R. R. Tenney, "A Case Study in Human Team Decisionmaking", Proc. Systems, Man, and Cybernetics Symposium, Tucson, AZ, November 1985.
- [5] K. L. Boettcher and R. R. Tenney, "On the Analysis and Design of Human Information Processing Organizations," LIDS-P-1503, Proc. 8th MIT/ONR Workshop on C³ Systems, December 1985.
- [6] K. L. Boettcher and R. R. Tenney, "Distributed Decisionmaking with Constrained Decision Makers - A Case Study," Proc. 8th MIT/ONR Workshop on C³ Systems, December 1985.
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